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# Earth's Future

## RESEARCH ARTICLE

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### Key Points:

- Systems thinking and interdisciplinary collaboration are needed, but the way humans reason about complex systems is often unacknowledged
- The Abstraction Hierarchy was developed to complement the natural line of human reasoning and overcome complexity “obstacles”
- The potential of this approach is demonstrated through an example Urban Systems Abstraction Hierarchy

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## Urban Systems: Mapping Interdependencies and Outcomes to Support Systems Thinking

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**Abstract** This paper argues that urban systems issues are design problems on a grand scale and that various disciplines aiming to address them can have only a partial view of the problem. It is necessary to draw boundaries around the detailed analyses of specific issues, but a way to map the wider system, to contextualize and more deeply understand how they are interrelated, is still lacking. Four complexity obstacles related to reasoning about complex systems are in our way, and to our knowledge no existing approach navigates them effectively. We propose a tool called the Abstraction Hierarchy as a way to do just this, in order to frame complex issues on a large scale, in a way accessible to all disciplines. To demonstrate the power of this systems model, the Abstraction Hierarchy is applied to an urban area. Through its application we demonstrate its capability to navigate all four obstacles and investigate previously unexplored space in urban systems research.

**Plain Language Summary** One of the main barriers to combating climate change is unpicking the complexity of the problem and avoiding solutions that work in one way and create problems in another. This is because scientists sometimes fail to acknowledge we are human beings, and human beings reason about complex problems in a certain way. The discipline of human factors is centered on this fact and offers a well-tested design tool which follows the natural line of human reasoning. This tool—the Abstraction Hierarchy—could be applied in a new way, and at a much larger scale, to understand climate impacts on entire cities.

### 1. The Need for a Pluralistic Framework for Urban Systems

Humanity faces a range of global environmental challenges. Researchers increasingly grapple with large systems that are not fully understood, outcomes that are not easily predicted, and single-discipline silos where interdisciplinarity is required. While interdisciplinarity is not a new concept, some technical disciplines (e.g., civil engineering) still struggle with the “‘discovery’ of interdependence and of the complex processes involving society and environment” (Fernandes & Rauen, 2016, p. 200). In this context, interventions often target “highly tangible, but essentially weak, leverage points (i.e., using interventions that are easy but have limited potential for transformational change)” (Abson et al., 2017, p. 30). Where this is acknowledged the emphasis is on theory; examples include Luhmann’s (1995) social systems theory and Ostrom’s social-ecological systems framework (McGinnis & Ostrom, 2014).

The difficulty of tackling these challenges lies in developing tools and methodological guidance that capture the rich interactions of natural, technical, and social parts, in a way that is accessible and useful to all (Bedinger, Beevers, et al., 2019).

There is a need for a unifying framework to navigate large complex systems, to cope with a continuing struggle around how to “do” interdisciplinarity. This is reflected in the differences between coverage of resilience and sustainability; the former is passive and more clustered and interconnected, while the latter is active but more dispersed and siloed (Zhang & Li, 2018). Interdisciplinarity in these areas continues to “fall short of expectations” (Schoolman et al., 2012, p. 67) both in research and in practice (Childers et al., 2015; Hedelin, 2019).

In the search for sustainable decision making, there is a need to understand paradigms and outcomes from across disciplines (Brandt et al., 2013; Hall et al., 2014), cut across multiple spatial scales (Bedinger, Beevers, et al., 2019; Elmqvist et al., 2019), capture a wide breadth of system dimensions (Brandt et al., 2013; Persson et al., 2018), and account for future change and system reorganization (Hall et al., 2014). The key to this is a

tool that acknowledges many partial views, without oversimplifying them, as the inherent pluralism of large-scale systems is bigger than any one discipline (Elmqvist et al., 2019; Mahmoud et al., 2018; Miller et al., 2008; Pohl, 2011).

An understanding of urban systems—to support future city-level planning and design—is increasingly in demand. The call for greater interdisciplinarity is becoming louder, particularly for urban research methods (International Expert Panel on Science and the Future of Cities, 2018; Prieur-Richard et al., 2018; Siri, 2016). New methods which assess “current drivers and interactions among natural, human-built, and social systems in urban areas as they impact multiple sustainability outcomes across scales” (Ramaswami et al., 2018, p. 6) are needed. Bai et al. (2018) call for a deeper understanding of future urban systems, specifically with regard to the interactions, trade-offs, and synergies and accounting for unintended effects, in a way which allows for working across disciplines. This paper begins by introducing four complexity obstacles that we believe are “blocking the path.” To help overcome them, we introduce the Urban Systems Abstraction Hierarchy.

## **2. Four Complexity Obstacles**

Examination of selected example approaches demonstrates how these four complexity obstacles manifest in large-scale systems research.

### **2.1. Obstacle 1: Language**

Communication across disciplines is key, but there is a trade-off. Specialized research is intended to deepen knowledge; on the other hand, research language may be siloed in such a way that paradigms and findings must be translated from one technical jargon to another. The more disciplinary knowledge and technical skill needed to replicate an approach, the less accessible and useful the underlying paradigm and results become.

### **2.2. Obstacle 2: Scale Versus Resolution**

Systems at large spatial scales can facilitate substantial change through high-level decision making—but also through interventions in key areas. Complexity literature calls such unexpectedly powerful and transformative interventions “lever points” (Holland, 2006), “leverage points” (Meadows, 2008), or “sensitive intervention points” (Farmer et al., 2019). In this endeavor, there is a trade-off between our ability to capture data at the physical or geographic scale and capture data at a sufficient resolution to reflect real-world behaviors and dynamics. In large complex systems, sensitive intervention points could be missed when using an approach with coarse granularity. It follows that “more data is better.”

In an ideal world, a “complete” model would include all possible observations of one type of interaction at a fine resolution; for example, a detailed biophysical model of water infrastructure performance. At larger physical scales, such as the city level, this amount of data becomes difficult to obtain and/or process. Therefore, in order to facilitate meaningful decision making, a coarser resolution of data is often used. To this end, an indicator or general rule of thumb might be used, for example, records of reported drainage problems throughout the city or making assumptions about all infrastructure within the city, based on a sample. For quantitative analyses, advances in data collection and computing power (big data or supercomputing) could enable the identification of “sensitive interventions.” These advances do not apply where fine-resolution data are not readily available; human behaviors outside of the current scope of internet-based activities represents one such example.

Thus, we identify Obstacle 2 as an issue of scaling up using a unidisciplinary approach: greater spatial scale at a fine resolution. Current boundaries relate to data resolution, availability, and our ability to process it. However, current boundaries are being stretched. The rise of social media, interconnected personal devices, the digital environment, and the Internet of Things shows high potential for collecting new kinds of data for a range of disciplines.

### **2.3. Obstacle 3: Breadth Versus Comprehensibility**

Where the key premise of Obstacle 2 is the focus on one type of interaction at a time, Obstacle 3 relates to several types of interactions, for example, building on the water theme: water infrastructure performance *and* urban development patterns *and* their dynamic interactions (e.g., feedback loops). The integration of

social, technical, and natural realms—as referred to by Ramaswami et al. (2018)—may serve to provide valuable new insights, for example, knock-on effects where one well-placed intervention might be optimized for multiple benefits. It follows that “more types of data are better.”

Increasing the types of interactions considered achieves the interdisciplinarity required of complex systems. This, in turn, challenges the researcher to define a system boundary, not in terms of spatial scale but of theoretical scope—the number of subsystems or types of interactions. The trade-off is between this breadth and the comprehensibility of system dynamics that are meaningful to overall system behavior. To take our water infrastructure example: Should the system dynamics under consideration be limited to biophysical aspects and urban development patterns? Perhaps societal needs and their relationship to services such as water supply are also important to consider. How broadly should we cast our net? At what point have we cast the net so broadly that we cannot identify the governing system dynamics for the phenomenon in question?

These choices, about where we draw system boundaries and what is meaningful to include in the analysis, are important and must be made, consciously or unconsciously. Traditionally, these choices rely on discipline-specific theory, potentially reinforcing the disciplinary siloes present in Obstacles 1 and 2. Supported systems thinking can prevent the omission of unexpectedly powerful influences on system behavior. This challenge is of particular importance when considering whether, and how, to integrate the intangible “social” aspects of cities with the natural and technical (Missimer et al., 2017; Olsson & Jerneck, 2018; Rogers et al., 2012).

#### 2.4. Obstacle 4: Change

In coping with the rapid pace of development, sociocultural change, technological advancement and climate change, we cannot fully know or predict every context and future state. Generalized approaches which may be easily updated are highly desirable. Change processes are beginning to be modeled for specific problems in specific contexts, using historical data as a starting point. This depth of analysis lends additional credibility to decision makers. However, local contingencies such as cultural and institutional settings are key, not just to understanding present-day conditions but also to assessing possible, projected, or target future scenarios.

#### 2.5. How the Four Complexity Obstacles Manifest in Research

In many domains, it is common to see a range of methods applied, with multiple method types cutting across different studies (Brandt et al., 2013; Hedelin, 2019). The choices behind what is, or is not, included in a combined approach illustrates important differences in how the subject is framed as a “systems issue.” Though a review of approaches in many topic areas could demonstrate these points, we continue with the water supply example, drawing from a recent review of methods for climate change adaptation to floods and droughts (Bedinger, Beevers, et al., 2019). These methodological choices include indicator-based methods, discipline-specific models, nexus approaches, and integrated assessments.

*Indicator-based methods* (such as Tran, 2016) involve a collection of isolated parts, focusing on system components rather than connections. They cover a broad scope but do not explicitly account for system interdependencies. While this method is a coarse, reductionist system representation (Waas et al., 2014), it does allow for wider replicability and understanding of the paradigm and results, and it can be easily generalized and adapted. In this way it navigates both Obstacles 1 and 4, but not 2 and 3.

Interdependencies are often captured through *discipline-specific models* that can be generalized across contexts when the underlying theory of a phenomenon is well understood; examples include natural systems modeling (Gao et al., 2018), economic modeling (Thacker et al., 2018), and agent-based modeling (Ali et al., 2017). Looking through the keyhole of a narrowly defined problem with such sophisticated methods is essential to get a sense of the complex system behind the door. Of course, when the metaphorical door is unlocked and opened, it is this wider framing which provides a clearer view of the whole system, one that is accessible to everyone along the breadth axis. For example, modeling the impact of glacier variation on water resources (as in Gao et al., 2018) necessarily excludes the numerous other influences on water resources (e.g., anthropogenic interactions as in Collet et al., 2015). No single method can be expected to “do it all.” Discipline-specific models are able to navigate Obstacle 2 at the expense of 1, 3, and 4.



Other approaches that require an “explicit and extensive consideration of sectoral interdependencies” (Smajgl et al., 2016, p. 535) are insufficient in breadth or are targeted to a specific context and audience. The water-energy-food nexus (e.g., Smajgl et al., 2016) is a good example of this. This approach begins with and emphasizes preconceived “core” disciplines, meaning that “our ability to untangle the water-energy-food nexus and make the approach operational is also limited by the lack of systematic tools that could address all the synergies and trade-offs involved” (Liu et al., 2017, p. 1718). The nexus is generated by experts, in general terms at a coarse resolution. This, however, is for a single geographic area and rooted in expert knowledge of how the “system” has worked in the past. By beginning, not ending, with a context-specific understanding it is difficult, and resource-intensive, to transfer the methodology to new contexts. Applications to alternative geographic areas, or future conditions with different operating rules, are limited. Thus, a nexus approach navigates Obstacles 1 and 3, but not 2 and 4.

The above represent a handful of approaches, with each addressing at least one of the four complexity obstacles identified. Current research problems often require *integrated assessments*, making use of multiple methods in tandem. However, the success of this strategy depends wholly on the ability of individual researchers to apply systems thinking, more or less unguided, while at the same time making decisions about which interdependencies to include and how to integrate multiple methods in a meaningful way. In view of the trade-offs—not just within the four obstacles, but also among them—we need a new way to navigate them. This means being bolder in venturing to foreign disciplinary frontiers and borrowing their conceptualizations of complex systems. We need a new framework capable of navigating and mapping interconnections within complex systems, otherwise outcomes such as sustainability and resilience will continue to be just out of reach.

The trade-off of spatial scale versus resolution, and the resources required to analyze them, is resolving itself through increasing computer power and the rise of big data. As such we are often able to identify—within a single sector or discipline—the interdependencies that matter within a large set of observations of narrowly defined phenomena.

The larger, and we would argue most significant, research challenge appears to be how we conceptualize and choose the types of interdependencies that matter (such as the theoretical aspects of system breadth) in our mental models of the system (Bai et al., 2016). Interdisciplinary understandings that can begin to deal with these complexities are relatively immature and contextual, thus hindering their ability to be generalized, address change, and integrate with methods that hold crucial disciplinary depth. This is further stalled by our lack of “multilingualism” across fragmented disciplines. What we need is an event-agnostic, pluralistic framework that can do it all. One such tool has presented itself. In the sections that follow, we explain the origins of this new tool, demonstrate how existing approaches can be mapped within it, and suggest how it can be used in a way that supports systems thinking for complex urban systems.

### 3. Cognitive Systems Engineering

Human factors and ergonomics (HF/E) develops the “theoretical and fundamental understanding of human behaviour and performance in purposeful interacting sociotechnical systems, and the application of that understanding to design of interactions in the context of real settings” (Wilson, 2000, p. 557). We recognize that the consideration of human behavior and eschewing of rational choice theory is not new—for example, there is much existing research on encouraging the public to adopt more sustainable behaviors. While HF/E principles have much to contribute in these areas, in this paper we argue they could be uniquely applied to a deeper level of science: the way that researchers understand and reason about complex systems.

Research into urban systems presents issues and challenges similar, conceptually, to some of those already encountered in HF/E. Climate change presents urban systems researchers with the possibility of new situations, previously unexperienced and thus largely unforeseen by our existing methods of analysis. Thus, we are naturally driven to adapt to the world we are working within, based on our own partial understandings of how that system works.

The only difference between traditional HF/E design problems and urban systems is one of scale. For urban research, the system moves out of the workplace, the factory or the plant and instead encompasses the entire city or region. Indeed, while the tradition of HF/E is in sociotechnical work systems, the field is continually

expanding. This includes work in natural systems (disaster risk resilience as in Le Coze, 2013), larger spatial scales (Karsh et al., 2014; Siemieniuch & Sinclair, 2014), more open systems (a high street as in Patorniti et al., 2018), and urgent global priorities (sustainability as in Radjiyev et al., 2015; Thatcher & Yeow, 2016).

All of this points to a discipline ready to contribute paradigms and tools to develop a shared understanding of large complex systems. We propose that HF/E has much to offer in navigating the four complexity obstacles. Specifically, HF/E principles around human reasoning make one tool—the Abstraction Hierarchy—a prime candidate for framing sustainability issues in a useful but novel way: as a design problem, albeit one on a grand scale.

#### 4. Reasoning in Complex Systems

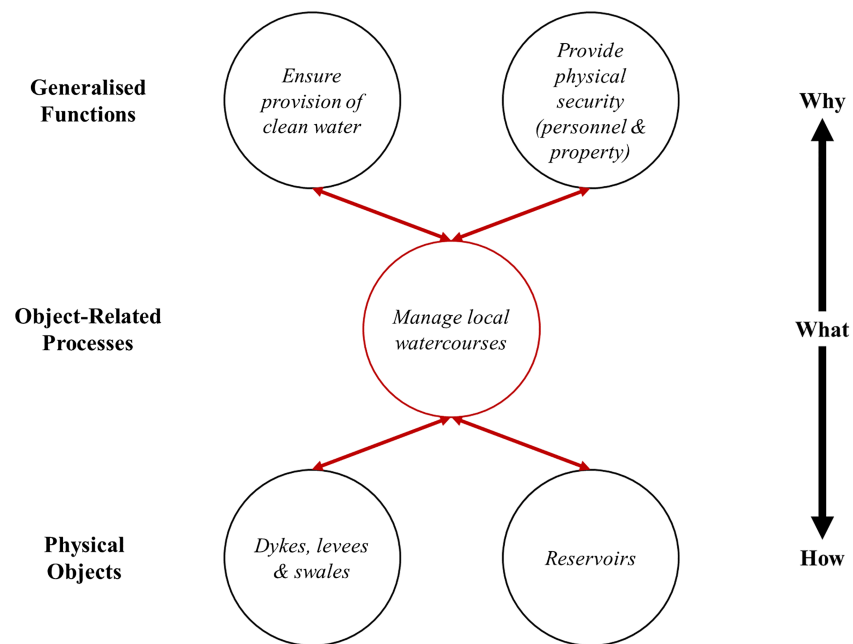
The systems perspective employed by HF/E is exemplified by early studies in the nuclear power domain (Rasmussen & Goodstein, 1987). This may appear at first glance to be a long way from the challenge of sustainability and resilience, but analysts encountered precisely the same obstacles of language, scale, resolution, breadth, comprehensibility, and change as evidenced in the complexity obstacles. In this case, the nuclear power plant's technical system met all its design requirements but only according to standard operating conditions and preplanned procedures. By ignoring variation and uncertainty beyond existing system requirements, designers were prescribing specific human behaviors around a “predictable” technical system, assuming “hyperrational” (Croson et al., 2013) workers. We see similar thinking in some climate change adaptation efforts in urban systems, for example, in engineering solutions that do not acknowledge human behavior or institutional memory.

Early HF/E work found that accidents occurred because the design approach failed to incorporate both the possibility of new situations and user adaptation to the systems they are working within. Indeed, experience revealed many more “heroic recoveries” than “human errors,” demonstrating that often the best system component for dealing with complexity was the human. How the workers reasoned about the system they were using (Naikar, 2017) was captured to leverage this. It was found they considered the following:

1. Different system scales at different resolutions, moving between coarse depictions of relatively large-scale properties and fine-grained depictions for smaller-scale properties. This is indicative of Obstacle 2.
2. The whole system at different levels of abstraction, fluctuating between abstract purposive understandings of why the system exists and physical understandings of what the system consists of. This is indicative of Obstacle 3.
3. The system along a diagonal reasoning space, where small-scale, fine-grained properties tended to be understood as physical and concrete, and large-scale, coarse-grained properties tended to be understood as purposive and abstract. This is the typical structure and line of human reasoning.
4. The system as event- and situation-independent, in such a way that different approaches to problem solving in a variety of scenarios could all be understood within a single reasoning space (Obstacle 4).

A framework based on human reasoning and adaptation to complex systems was developed by Rasmussen et al. (1994), using simple nontechnical language (Obstacle 1). The first stage, the Abstraction Hierarchy (AH), established a way to use the above insights and “represent information about the properties of the system ... in a way that is both compatible with the characteristics of human problem-solving and event-independent” (Rasmussen & Goodstein, 1987, p. 530). The AH “addresses not only what is performed, but also, how and why” (Jenkins et al., 2009, p. 18) and illustrates the structural degrees of freedom available in the system to achieve higher-level purposes (e.g., sustainable development) (Naikar, 2017). The output represents how the “user”—in the case of urban systems, a member of the public, a decision-maker, or a researcher—views the system they are operating within. By avoiding reliance on a structure of specific actions, the system can be understood outside of everyday requirements, even for unanticipated events (Naikar et al., 2005). In other words, the framework goes beyond the study of what should or does typically happen, to examine what could happen.

The insights gained through the AH enabled workers to successfully adapt their behavior in unforeseen situations, thus “finishing the design” of the system (Radjiyev et al., 2015). This set a guiding principle: Effective design goes beyond the technical, recognizing that phenomena arise from systems not components (Russ et al., 2013; Salmon et al., 2015), and humans are one interacting part. These principles, and



**Figure 1.** Why-what-how relations in the Abstraction Hierarchy, using the example node *Manage local watercourses*.

Rasmussen's insights around the structure of human reasoning, are instructive beyond the confines of nuclear power. If urban systems are a large design problem, and the AH a tool for confronting the obstacles of a true systems approach, then the question arises: How can this be applied on a grand scale?

## 5. Method of Application

The Abstraction Hierarchy (AH) is a systems map. The system is decomposed into discrete parts (nodes) at five different levels of scale. These nodes are linked between the AH levels, not within them; by their functionality rather than their physical connectivity. The links are as important as the nodes, because they represent “the ‘means’ that a system can use in order to achieve defined ‘ends’ ” (Beevers et al., 2016, p. 203), explicitly connecting the physical and abstract.

The functions in the AH are increasingly abstracted at each level. The bottom level contains classes of “Physical Object” within the system boundaries. The next level up, “Object-Related Processes,” explains what each of these objects can physically do, describing their capabilities and limitations. The third level, “Generalized Functions,” shows what tasks can be accomplished by using these specific processes. “Values and Priority Measures” are the fourth level, representing criteria by which we can determine if a system is fulfilling its “Functional Purposes,” the top level of the hierarchy that identifies the fundamental reasons why the system exists.

The AH is also bidirectional. Given a specific node anywhere in the hierarchy, working upward answers the question of why that node exists; traveling downward answers the question of how that node contributes to achieving a higher-level function. This can be seen in Figure 1, where the “Object-Related Processes” node *Manage local watercourses* is extracted from an AH for urban areas. In the level above, *Manage local watercourses* is linked to two “Generalized Functions”: *Ensure provision of clean water* and *Provide physical security (personnel and property)*. Managing local watercourses is a process that exists to both provide clean water, and protect people and property (from flooding). In the level below, *Manage local watercourses* is connected to two “Physical Objects”: *Dykes, levees, and swales* and *Reservoirs*. Managing local watercourses is achieved through use of either, or both, of these “Physical Objects.”

The AH is constructed in consultation with subject matter experts, using a series of prompts to populate the hierarchy with nodes and make connections between levels. For example, one prompt used to populate the “Physical Objects” level is *What are the physical objects or physical resources in the work system—both man-made and natural?* (Naikar, 2017). Answers are recorded by an HF/E analyst to create a

visualization of the AH, which is later presented and discussed with experts for validation, and this cycle is performed iteratively until no additions or changes are suggested.

While HF/E offers much to urban systems issues, the AH is proven to be particularly effective in integrating “partial view[s] of the design problem” (Burns & Vicente, 2000, p. 79). Patorniti et al. (2018) applied the AH to an Australian high street and after including a spectrum of stakeholders they found “without such an approach, the range of inputs for a main street system would not be captured” (Patorniti et al., 2018, p. 293). Thus, the AH is a proven way to unify and explore multiple perspectives across disciplines.

The AH takes the interdependencies of a nexus approach (e.g., Smajgl et al., 2016) to an entirely new level. Notably, other sustainability researchers have begun developing similar frameworks completely independent of HF/E efforts, heeding the subconscious call to incorporate interdependencies across both system scale and system breadth. However, some (e.g., Maher et al., 2018) treat abstract and value-based properties as separate from a physical system, despite clear calls for integration (Prieur-Richard et al., 2018). Others (e.g., Webb et al., 2018) tell us more about what kind of interactions a model should emphasize, rather than the specifics of what these interactions are, to remain accessible and generalizable. In contrast, the AH affords coverage of all of these elements.

We propose that the AH can be applied to effectively frame and strategize issues in complex urban systems. The AH accounts for unintended effects among system parts, in a way that is accessible across disciplines (Obstacle 1), with broad scope (Obstacle 3), and across multiple spatial scales in a way that can leverage integration of higher-resolution discipline-specific methods (Obstacle 2). Critically, the AH is adaptable and flexible in the face of new contexts, technologies, and functions (Obstacle 4). Its main limitation is its initial user-friendliness. Once familiar with the method, analysts and stakeholders deem it a usable toolkit (Read et al., 2018), and this familiarity can be facilitated through improved visualization and wider dissemination. This perspective serves to enable this, through a specific example: an AH for urban systems.

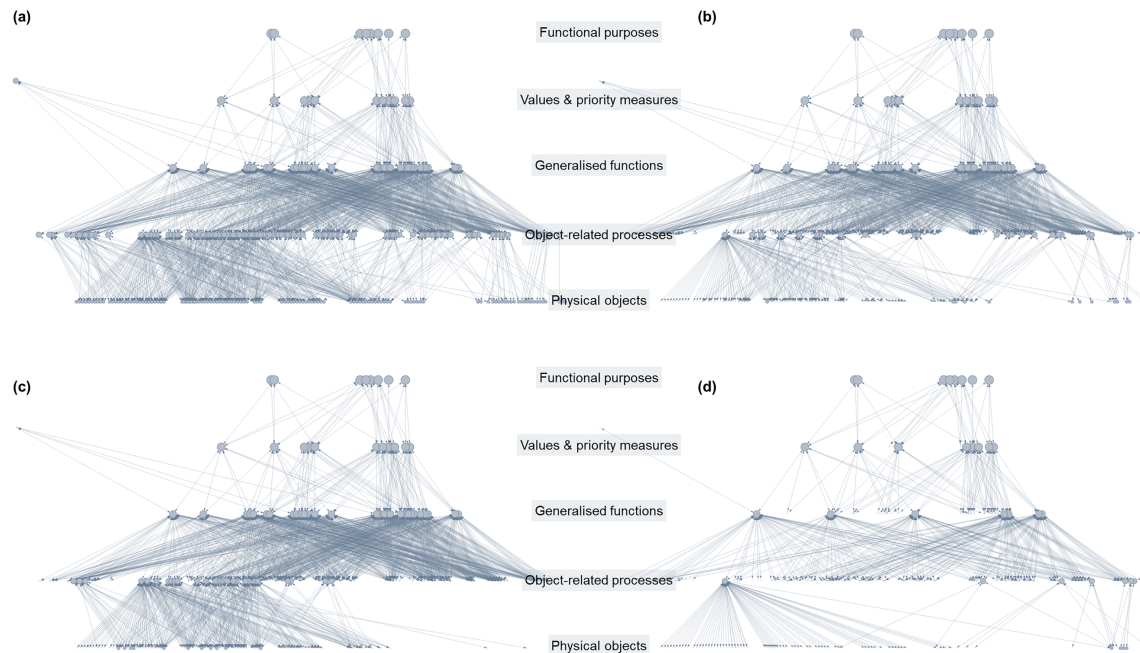
## 6. A City-Level Example

To illustrate how this can be applied on a grand scale to navigate the identified complexity obstacles, we present an application to an entire city. This AH was developed from flood vulnerability research (Beevers et al., 2016) and expanded through literature review and expert consultation (city planners, policy makers, environment agencies, and other stakeholders). Given the scale of this Urban Systems Abstraction Hierarchy (USAH), an interactive visualization is available (Bedinger, Visser-Quinn, et al., 2019), facilitating exploration in greater detail. The reader can zoom and navigate the USAH, hover to view node names, select nodes to view their connections, use the drop-down menu to view subnetworks, and export.png images of the USAH.

Below we provide a general overview and a few illustrative examples of the content of the USAH. Each example begins with a concrete, physical object and runs through the hierarchy to show functional connections to increasingly abstract levels:

1. **Physical Objects.** Lowest level of the USAH, includes buildings, infrastructure, and natural features within an urban area
2. **Object-Related Processes.** What the objects physically do, such as *Generate energy* or *Act as a community meeting space*
3. **Generalized Functions.** What tasks and services can be accomplished by using these specific processes (2), such as *Provide clean water* or *Enable social interaction*
4. **Values and Priority Measures.** Criteria by which we can determine if the city is fulfilling its purposes, such as *Provide critical services* or *Safeguard human health*. In this work, the Values and Priority Measures are based on the 12 goals of the 100 Resilient Cities project (Arup, 2015), rather than the UN Sustainable Development subgoals for Sustainable Cities and Communities (United Nations, 2019), in part because these are “largely silent about interlinkages and interdependencies among goals” (Stafford-Smith et al., 2017, p. 911).
5. **Functional Purposes.** Top level of the USAH. Identifies core reasons for the existence of any city. These also represent reasons why an individual might consider building, living in, or migrating to an urban

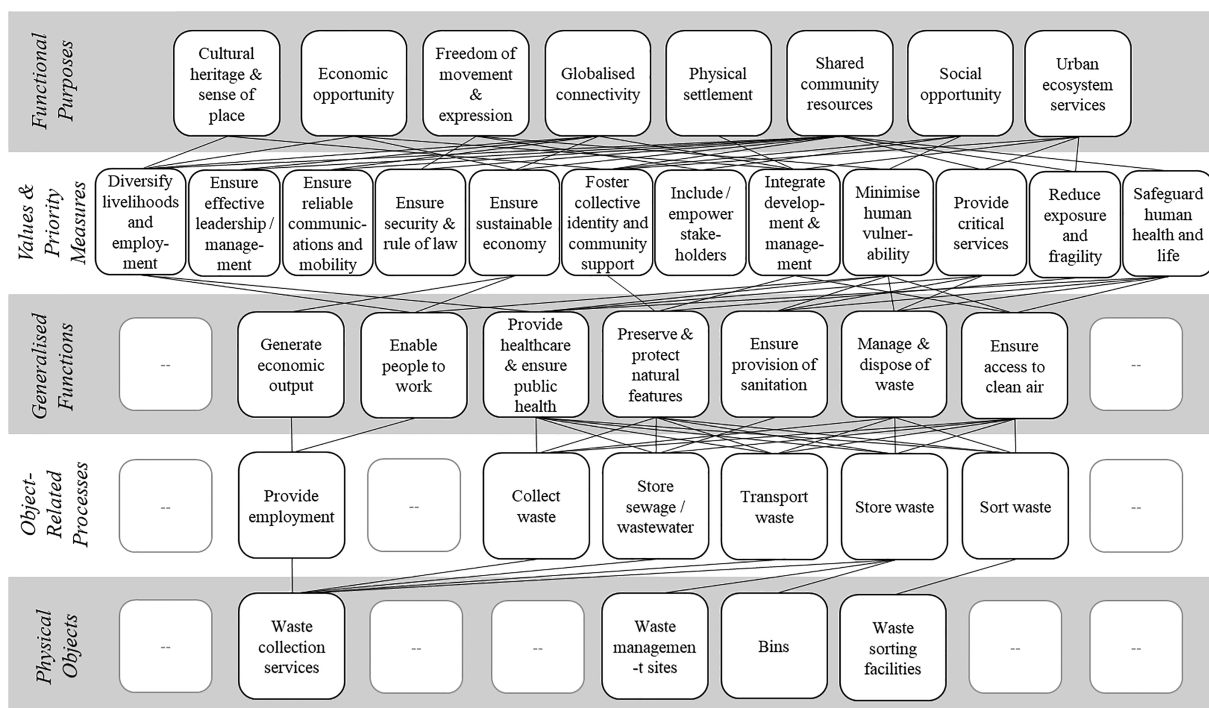




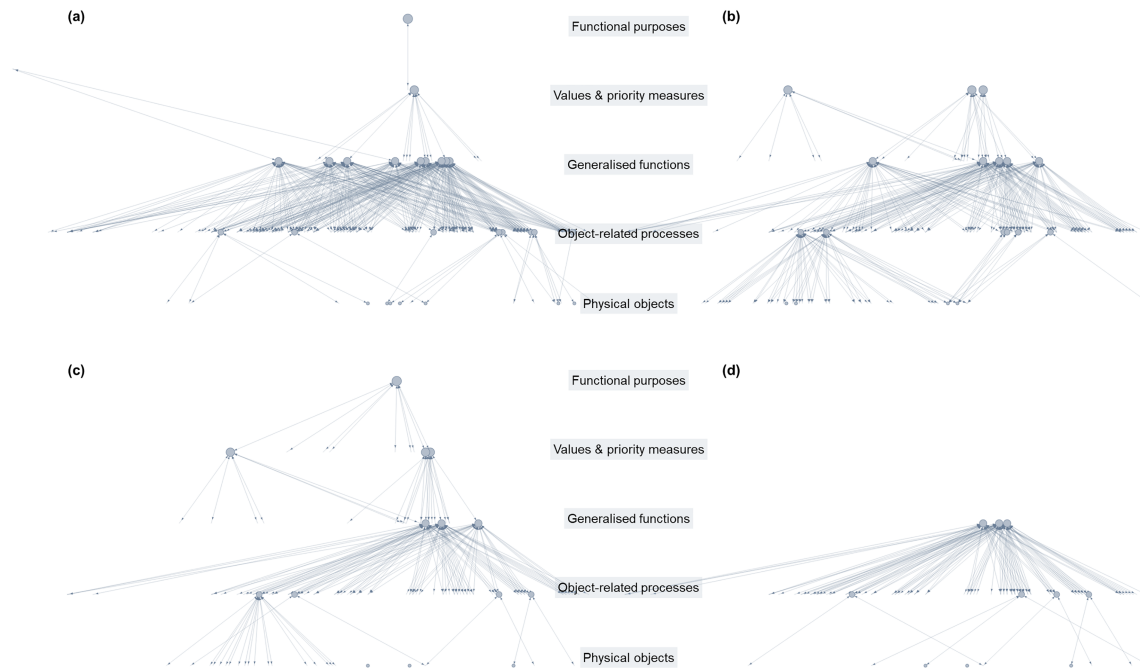
**Figure 2.** Different disciplinary theme subnetworks in the Urban Systems Abstraction Hierarchy including (a) all nodes, (b) water, (c) cultural, and (d) waste management.

area. In our city example these are *Cultural heritage and sense of place*, *Economic opportunity*, *Freedom of movement and expression*, *Globalized connectivity*, *Physical settlement*, *Shared community resources*, *Social opportunity*, and *Urban ecosystem services*.

As a first example, we consider the “Physical Object” node *Power stations*. This node is one of several Physical Objects relevant to energy provision. It is connected to two “Object-Related Process” nodes



**Figure 3.** Waste management subnetwork within the Urban Systems Abstraction Hierarchy.



**Figure 4.** Different research approaches to urban water supply mapped to the Urban Systems Abstraction Hierarchy including (a) Rauch et al. (2017), (b) Tran (2016), (c) Liu et al. (2017), and (d) Ali et al. (2017).

(Level 2), which explain that a power plant enables the processes *Generate energy* and *Store energy*. Highlighting the importance of interconnectivity, these two nodes are connected to every Level 3 node. This is because energy is required to perform almost every city function, from *Provide emergency services* to *Conserve environmental assets*. Consequently, these connections propagate up the abstraction hierarchy, linking to all 12 “Values and Priority Measures” and all eight “Functional Purposes.” These levels constitute the intangible components of the energy infrastructure system. By removing any node in this subnetwork, it may lose overall functionality—potentially in ways that affect other subnetworks.

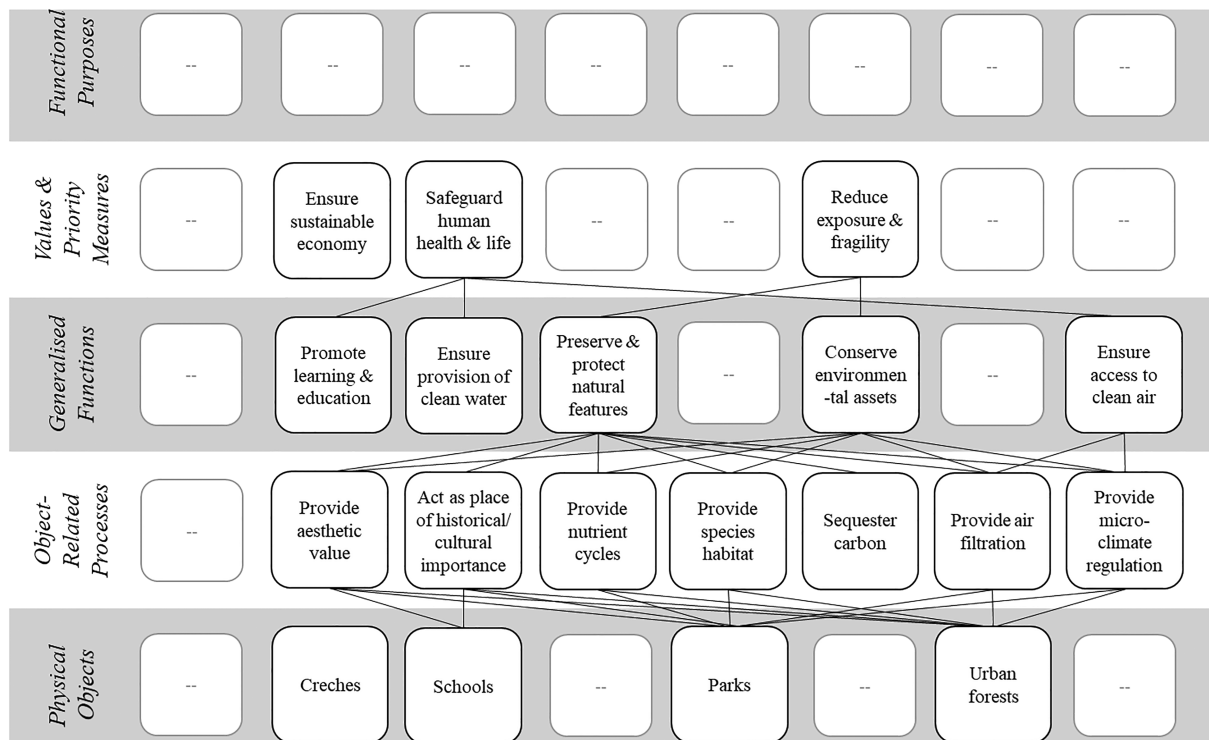
Another example is the “Physical Object” node *Religious buildings*. This is one of several Physical Objects that are relevant to culture. It is connected to 11 “Object-Related Processes,” for example, *Perform memorial and burial services*, *Act as community meeting space*, and *Provide employment*. These nodes enable a further 12 Generalized Functions, for example, *Perform ceremonies and services for major life events*, *Enable social interaction*, and *Enable people to work*. At this stage there are various pathways connecting to all of the “Values and Priority Measures” and “Functional Purpose” nodes.

The above examples describe how a single “Physical Object” fits in to the urban system. The USAH nodes at all levels could also be classified into sets based on object owners, disciplinary themes, or specific research studies. Figure 2 demonstrates differences in USAH coverage if “Physical Objects” are classified into disciplinary themes such as culture, economy and finance, energy provision, healthcare, nature, transport, waste management, and water. These classifications are not exhaustive, but show that by focusing on just one subnetwork, we may miss critical interdependencies within the wider system. Figure 3 shows a single example of the waste management subnetwork, with labeled nodes for closer inspection.

Figure 4 compares four studies identified through the recent comprehensive literature review of methods for climate change adaptation to floods and droughts (Bedinger, Beevers, et al., 2019). Described below with reference to the complexity obstacles, Figure 4 clarifies how partial views of the system reside within the USAH.

The first example is an indicator-based approach to sustainable urban development (Tran, 2016), which can be seen with labeled nodes in Figure 5. This study includes both physical processes (e.g., *Reduction in median load of nitrites and nitrates*) as indicators of water quality and natural health, and municipal data (e.g., *Number of schools*) as distal measures for recreation, culture, and esthetics. While indicators cover both





**Figure 5.** How an example research approach to urban water supply (Tran, 2016) maps to the Urban Systems Abstraction Hierarchy.

concrete and abstract elements of the system—system breadth—some of the commonly accepted sustainability goals highlighted in our “Values and Priority Measures” are missing (e.g., *Minimize human vulnerability*). Furthermore, a number of interdependencies between nodes are not explicitly covered (i.e., links are highlighted but their destination nodes are faded). For example, the indicator “Value of health, ecosystem, and materials damage avoided due to carbon monoxide removed” corresponds to the “Value and Priority Measure” *Ensure a sustainable economy*, but none of the nine nodes connected to this are addressed by the study. This navigates around both Obstacles 1 and 4, but not 2 and 3.

The discipline-specific models (Ali et al., 2017), shows an intensified focus on the center of the USAH (Figure 4). Some interdependencies at the “Physical Objects” level are ignored because due to a higher level of scale (a water balance model), which requires less detail around physical objects and processes (versus a hydrological model). Instead, the authors take an in-depth view of decisions centering on “Object-Related Processes” (e.g., *Manage local watercourses*) and trade-offs between their links to “Generalized Functions” (e.g., *Ensure access to clean water* vs. *Conserve environmental assets*). This navigates around Obstacle 2, but not 1, 3, or 4.

If we examine an integrated assessment, the example of Rauch et al. (2017) shows particularly good USAH coverage (Figure 4). The approach unintentionally follows Rasmussen’s structure of human reasoning, by using several models to understand sections of the USAH, and integrating the models where those sections overlap. A societal transitions model (e.g., de Haan et al., 2016) considers interdependencies between societal needs and services, occurring in the upper three levels of the USAH (“Functional Purposes,” “Values and Priority Measures,” and “Generalized Functions”). The urban development model (Urich & Rauch, 2014) analyses housing development, land use, and water infrastructure interactions that trend to the center (“Generalized Functions” and “Object-Related Processes”). The biophysical model (Bach et al., 2013) analyses detailed water infrastructure processes at the lower levels of the hierarchy (“Object-Related Processes” and “Physical Objects”). Together this results in good USAH coverage with in-depth methods (navigating Obstacles 2 and 3 relatively well), but it is also highly specialist (Obstacle 1). Despite its aim to understand the dynamics behind system transitions from a starting point, it is resource-intensive to generalize and adapt to new contexts (Obstacle 4).

The nexus approach (Liu et al., 2017), reaches into the upper levels of the USAH but neglects related “Object-Related Process” and “Physical Objects” nodes (see also Figure 4). For example, the “Functional Purposes” node *Shared community resources* is included, while the “Physical Object” *Water pumping stations* is disconnected. Interdependencies between levels are often incorporated but neglect dynamics outside of water, energy, and food; for example, the “Generalized Functions” *Provide healthcare services* and *Generate tourism*. This navigates around Obstacles 1 and 3, but not 2 and 4.

These specific subnetworks and studies each contribute a partial view of the system within the wider USAH. No single research approach is expected to address the entire system, but it is clear that all of the above examples fit within the larger system view afforded by the USAH for urban systems. If some peripheral interdependencies must be neglected, the USAH is capable of the scope required to shed light on them. This enables clearer discussions around their inclusion or exclusion, and demonstrates the USAH's potential to overcome the four obstacles.

## 7. A Pluralistic Framework

This paper argues that, in order to progress research concerned with future urban design, we need to support systems thinking, by navigating four obstacles: language, scale versus resolution, breadth versus comprehensibility, and change. These have been tackled before, albeit at a much finer scale, within HF/E. Using Rasmussen's findings as a scaffold, we propose that expanding the AH to a previously unseen scale allows researchers to navigate complex systems in a structured, consistent, coherent, replicable, pluralistic, and interdisciplinary way. While our USAH is not a *fait accompli*, adjustments, additions, and exclusions are in progress (all of which require wider interdisciplinary dialog). The presented USAH offers a template for urban systems thinking, to navigate the four complexity obstacles (Figure 6).

### 7.1. Obstacle 1: Language

By combining the multiple partial views of the system in a consistent, coherent way a multilingualism of complex systems is constructed across communities and disciplines.

### 7.2. Obstacle 2: Scale Versus Resolution

Although it does not explicitly account for a large volume of system detail, the AH allows the researcher to “zoom in” or “out” of the system map to provide that detail with disciplinary methods where appropriate. The framework provides the scaffolding which supports the “slotting in” of detailed technical or process models. Thus, disciplinary depth and specialization is not neglected by the framework, rather it can be embraced and better strategized. For example, a water balance model might be connected to the linkages shown in Figure 1 to provide greater detail around how these are specifically performing.

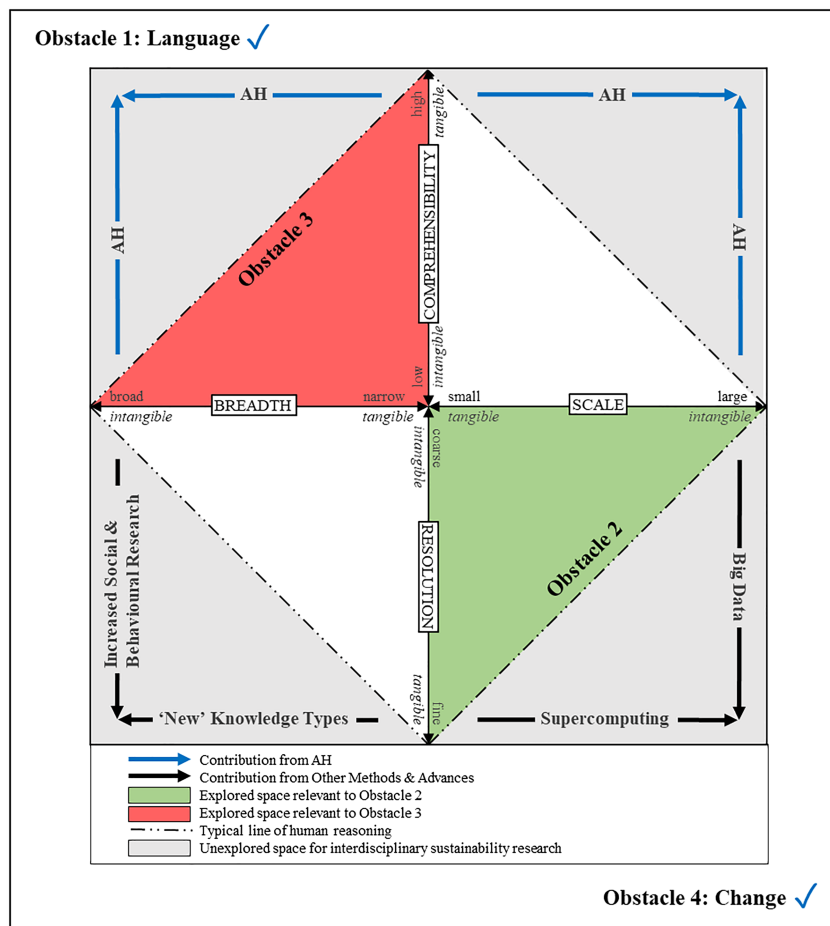
### 7.3. Obstacle 3: Breadth Versus Comprehensibility

A wide breadth of system dimensions is covered by the AH, including natural-socio-technical interactions, and value-laden system components. The AH allows for reflexivity, as it is epistemologically and methodologically agnostic. It can combine problem- and solution-oriented approaches (von Wehrden et al., 2019), recognizing that “methods are independent of the transdisciplinary process phases and knowledge types” (Brandt et al., 2013, p. 1). Thus, the AH is pluralistic, building a systems understanding that is inclusive, and valuing the unification of compatible views rather than forcing uniformity.

### 7.4. Obstacle 4: Change

The AH is time- and event-independent, such that it can be easily adjusted for new contexts or future scenarios. Its functional representation is flexible to changing technologies and practices. It provides a single system model with which we can conceptualize adjustments for local context, exposure to shocks versus stressors, push and pull dynamics between top-down design and bottom-up emergent behavior, and proposed interventions before they are implemented.

Figure 6 illustrates these obstacles for navigating complex systems and the typical lines of human reasoning around such systems. These lines constitute the underlying reasons for Obstacles 2 and 3 and are thus boundaries to unexplored spaces for interdisciplinary sustainability research. In the gray space we can see



**Figure 6.** How the Abstraction Hierarchy pushes the boundaries of interdisciplinary sustainability research.

where the AH, with the help of other approaches, can facilitate interdisciplinary sustainability thinking “outside the box.”

Big data and high performance computing have accessed some unexplored space in Quadrant 3. Acknowledging “new” data types (e.g., indigenous knowledge) alongside investment in social sciences research allows access to unexplored space in Quadrant 4. The AH framework complements these methodological and technological advances, while enabling exploration of the deeply uncertain space in Quadrants 1 and 2.

## 8. Future Directions

By viewing urban systems as a design problem, the USAH supports systems thinking, navigating the four complexity obstacles. It provides a tractable, unifying point of reference for all disciplines. There are many ways to use this framework and develop it beyond a generic conceptual map, including but not limited to the following:

1. Network analysis to prioritize interdependencies and explore the shape and structure of sustainability and resilience
2. Adjustments to reflect local context, using municipal data alongside local knowledge
3. Linkage of discipline-specific methods to subsections of the USAH to incorporate greater resolution, for example, detailed process models for water supply or public transportation
4. Scaling up or down to global or household levels depending on the research problem
5. Introduction of extreme natural events, or latent social vulnerabilities, to explore impacts—including forecasts of how these may alter in the future due to climate change

6. Trialing of proposed climate change adaptations, to analytically prototype how interventions (whether they be technical, social, or policy-driven) might affect the urban system, before they are implemented
7. Identification of key areas of the USAH such that we may delve deeper than the “what” and “how” of system functionality, using additional methods to ask questions about “who” is in the system and what their capabilities and limitations may be (in line with Cutter, 2016)
8. Harnessing the use of functional interdependencies to expand urban metabolism theory in a way that acknowledges the intangible (Cespedes Restrepo & Morales-Pinzon, 2018; Dijst et al., 2018)

Overall, we propose the USAH as a unifying reference point, to guide discussions of interdependencies at the periphery of specific disciplines. This support for systems thinking can only improve the “design process” for achieving future outcomes such as sustainability and resilience in urban systems. The power and flexibility of this framework affords vast opportunities for researchers and practitioners of all types, creating exciting new opportunities for research as a whole, by directly addressing our currently inadequate mental models for urban systems (Bai et al., 2016).

### 8.1. Get Involved

We welcome any interest in discussing, critiquing, or contributing to further development of this pilot Urban Systems Abstraction Hierarchy (Bedinger, Visser-Quinn, et al., 2019). A questionnaire has been developed specifically for this purpose; it is available on request through the corresponding author.

## Funding, Code and Data Availability, Ethics, and Conflicts of Interest

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